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The possible contribution of agricultural crop residues to renewable energy targets in Europe: A spatially explicit study ☆

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ABSTRACT

This paper provides a geographical assessment of potential bioenergy production in the European Union from residues of eight agricultural crops (wheat, barley, rye, oat, maize, rice, rapeseed and sunflower). The evaluation is geographically explicit at the scale of 1 km^2 and is based on two main computational steps. In the first step the amount of crop residues resulting from statistical assessment based on the methodology developed by Scarlat et al. [1] have been spatially allocated on the EU-27[1] territory using several auxiliary geospatial layers describing, for example, land cover, expected biomass productivity derived from soil parameters, climatic zones and topographical conditions. In the second step the number of model power plants (i.e., plants with a size of 50 MW thermal input and a raw material demand of about 100 kt/yr might be conveniently fed with available crop residues was estimated on the basis of two different allocation strategies implying a different grade of optimization.

The results show that the estimated crop residue resources in EU-27 could provide fuel for about 850 plants expected to produce about 1500 PJ/yr. Mobilization needs for the residues are also estimated, leading to a total amount of 1.5×10^{12}–2×10^{12} tkm are necessary for the full potential exploitation.

Contents

☆ The views expressed in this paper are purely those of the writers and may not in any circumstances be regarded as stating an official position of the European Commission.

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[1] The EU-27 expression symbolizes the current status of EU enlargements. Further information: http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Glossary:EU-27.

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1. Introduction

In 2010, about 62% of renewable energy in the European Union (EU) was generated from biomass and even if this share is expected to decrease to 57% in 2020, the total contribution of bioenergy to the EU mix is expected to increase form 3600 PJ in 2010 to about 5900 PJ in 2020 [2]. Bioenergy corresponds to the production of energy from three main categories of feedstock (agriculture, forestry and waste) for three main uses (transport, heat and electricity). In the European Union, targets for 2020 have been set in the Directive on the promotion of the use of energy from renewable sources (2009/28/EC).[2] The objective of this EU Renewable Energy Directive (commonly called the RED) is to establish a framework for the promotion of energy from renewable sources, with a view to achieve the target of a 20% share of renewable energies by 2020 and to reduce of 20% the GHG emissions, with 10% of renewables in the transport sector. Other countries in the world are aiming to develop their renewable energy sector. In this general framework, the issue of the use of crop residues for energy purposes or in biorefining operations is increasingly addressed and their use is expected to provide a significant contribution in order to avoid competition for resources and land use between bioenergy and biofuels production, food production and wood. This topic is presently of interest for the EU, but also for countries outside the EU, e.g. Brazil with a large resource of sugar cane straw, in addition to the bagasse [3], and China [4]. A number of studies has estimated the potential of different biomass residues available for energy conversion. Most of the studies addressing biomass potential from agriculture are based on country statistics for agricultural crops and include different feedstock. A more limited number of studies provided geographical information on biomass production areas together with a picture of the local availability of residues for energy uses.

Our dual-purpose study aims to give a clear, geographical overview of the potentially available resources of main arable farming crops in Europe, and to provide a methodology and dynamic model for optimal localization of straw-fed power-plants.

1.1. *Agricultural residues potential for energy production in the EU: a literature survey*

Estimates arising from different statistical and methodological approaches show relevant differences. Most recent researches covering the EU region are briefly summarized hereafter.

According to the study conducted by Nikolaou [5], the total bioenergy resource potential of agricultural crop residues (straw from cereals, stalks from maize, rapeseed and sunflower, vineyard and olive trees pruning) has been estimated to consist in 1370 PJ for EU-27. The straw and stalk residues were estimated on the basis of a constant grain/yield residue ratio, differentiated for crop types and between central, northern and southern European countries.

The study of Siemons et al. [6] provided the bioenergy technical potential of crop residues (wheat, barley, maize, sunflower, rapeseed, olive trees and vineyards) for all member states (MS). The estimations were made on the basis of cultivated area or production for each crop for the year 2000, an average product to residue ratios or residue yields derived from literature and an availability factor of 30% for all agricultural residues. The potential primary energy production of crop residues was estimated in this way at 1540 PJ for 2010 and 1670 PJ for 2020 in the EU.

The study carried out by Ericsson and Nilsson [7] at the level of MS provided the (theoretical) technical potential of agricultural residues from wheat barley, rye, oats and maize. This assessment is based on the average cereal and maize yields for 1998–2002 and assumes a residue generation ratio for the group of cereals and for maize residues. It also supposes that one quarter of the residues can be harvested and one-third of the harvested straw is used in animal farming. The study includes five scenarios for short, medium and long terms, based on the average cereal and maize crop yields for 1998–2002 period while an increase of yields (40% and 100%) was also assumed for some countries. This study estimated the potential primary energy provided by these residues to be between 620 and 930 PJ/yr, with the precise estimates varying over time due to assumed yield increases and due to the crop area reductions for the benefit of dedicated energy crops.

The biomass resources assessment, performed within the European project “Renewable Fuels for Advanced Powertrains—RENEW” [8] included agricultural crop residues at the national level and regional level in two scenarios, representing intensive biomass production based on minimal and high level of inputs for 2020. It considers a future crop production with either lower or higher rate for residues removal from land and for the percentage of straw used for animal farming. The crop residues considered include cereal straw (wheat, barley and rye), oilseeds straw (rape seed, sunflower and soya) and maize straw. Total straw production is based on total cereal production data for the years of 2000–2004. The mass ratio of the most common crop of a given group was used for the calculation. The RENEW project estimated the agriculture crop residue primary energy potential in the EU-27 at 1570 or 1480 PJ depending on the scenario considered.

The European Environment Agency (EEA) [9] provided an environmentally-compatible potential for the biomass that could technically be available for energy production for years 2010, 2020, and 2030 in EU-25, at a national level. The study includes residues and by-products from agriculture (solid agricultural residues: straw, stalks from sunflower and prunings from vineyards and olive trees); and other agricultural residues (manure and food processing waste). Future development is determined by scenario assumptions on socioeconomic developments and a set of environmental criteria. The EEA estimates for all residues and by-products from agriculture to reach 4180 PJ in 2020 and 4280 PJ in 2030 for EU-25.

The study of Noord et al. [10] provided an assessment of biomass potential for energy production, including agricultural residues for EU-15 plus Norway and Switzerland. The estimations are based on the data provided by Refs. [11,12] for residue yields. In estimating the availability of residues their different uses

[2] Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=Oj:L:2009:140:0016:0062:en:PDF.

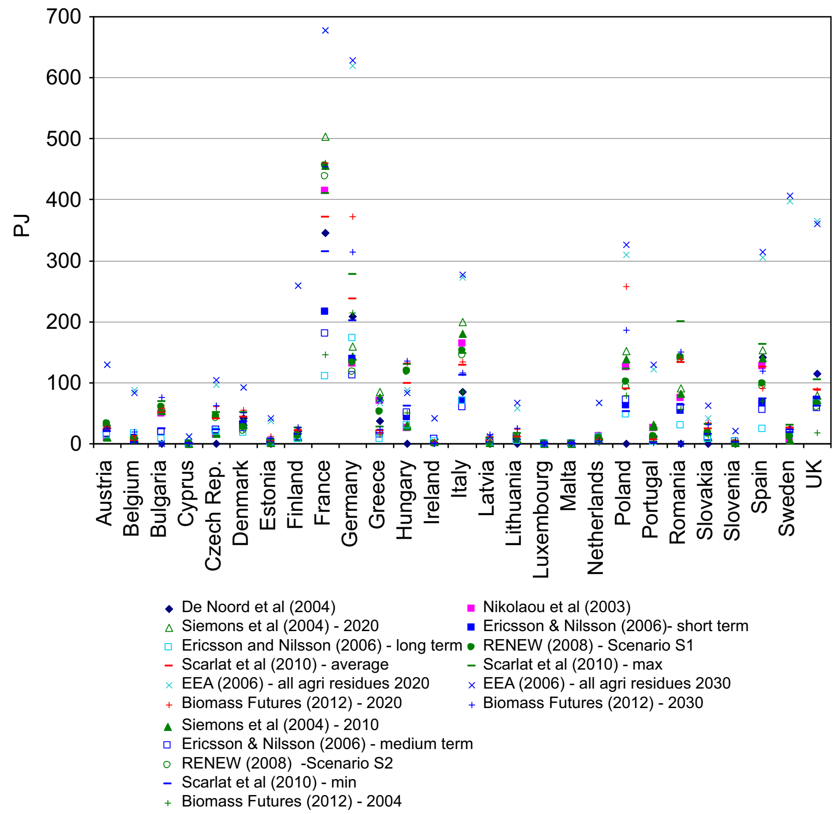

Fig. 1. Various assessments for crop residue potential and availability in the European Union. See text for details on each assessment.

(fodder, fertilizer and/or soil conditioner) were also taken into consideration and a fraction of the remaining residues was considered available for energy purposes (50% for straw and 25% for maize residues). A distinction was also made between Northern/Middle European countries and Southern European countries. Overall, the estimated primary energy potential of crop residues for EU-15 was estimated at 1100 PJ.

The study conducted by Edwards et al. [13] used both statistical and GIS (geographic information system) data to assess the energy potential of straw from wheat and barley in the EU. The straw produced was calculated on Eurostat NUTS2 level[3] and the major competitive uses were subtracted. The straw yield was estimated as a function of the grain yield based on the data from [14]. The straw used per head of cattle was calculated with an empirical equation and net straw availability data were then disaggregated using CORINE[4] land cover for 5 km × 5 km grid. The study showed that in EU-27 about 67 Ely-sized power plants (38 MWe capacity) could be built. Thus, the straw potential power energy utilized would be 230 PJ out of a total net straw availability of 820 PJ.

Crop residues availability for bioenergy use has been recently assessed at the EU-27 country level by Scarlat et al. [1]. In this paper, the mean, maximum and minimum amount of straw and residues available from eight crops (wheat, barley, rye, oat, maize, rice, rapeseed and sunflower) were estimated. This study considered residues to product ratios, derived from existing literature, depending on crop type and crop yield. Furthermore, other factors involved in straw availability such as environmental constraints and competitive use from farming were considered, leading to a statistical evaluation of the overall straw resources in European Union member states. The average amount of crop residues available for bioenergy in EU-27 was then estimated to be on average at 1530 PJ/yr, with a range between 1090 and 1900 PJ/yr.

The Biomass Future Project [15] provided an estimation of the straw potential in the EU, at regional level, based on the CAPRI[5] 2020 baseline and 2030 reference scenario on land use developments, following the JRC approach [13]. Biomass Futures study considers sustainable harvest levels aimed at maintaining the soil carbon levels in the soil and competitive uses of straw for livestock, using the CAPRI 2020 and 2030 livestock production per region. The results show that the total straw potential is expected to increase from 960 PJ in 2004 to 2064 PJ in 2020 and then to reach about 1990 PJ in 2030. This evolution incorporates the changes in the cereal production and livestock numbers predicted by CAPRI model. The study predicts a significant potential, mainly in France, Germany, Poland and Italy and predicts large increase in potential until 2030 in France, Poland, Germany, UK and Romania.

The results of reviewed studies on straw potential in different EU member states are presented in Fig. 1.

Most of the studies mentioned above for the straw potential assume a constant product to residue ratios and an average sustainable straw extraction. However, the sustainable extraction rate is highly variable at regional level, depending on the soil quality, climate conditions and management practices. Although the studies provided similar pattern of the distribution of straw potential in

[3] The NUTS classification (Nomenclature of Territorial Units for Statistics) is a hierarchical system for dividing up the economic territory of the EU. Level 2 contains the basic regions for the application of regional policies.

[4] Coordination of Information on the Environment (CORINE) is a European program initiated in 1985 by the European Commission, aimed at gathering information relating to the environment on certain priority topics for the European Union (air, biotopes, coastal erosion, land cover, soil, water, etc.).

[5] Common Agricultural Policy Regionalised Impact Modelling System (CAPRI), more information: http://www.capri-model.org.

different countries, there are significant differences between the results, depending on the different assumptions considered. There are additional uncertainties in the availability of straw supply for energy production. These relate to the variability in relation to crop type cultivation, due to the changing market conditions, as well as to the competitive uses of agricultural residues, including the different energy uses of biomass (heat, electricity generation, and biofuels), biochemical and other bioproducts [16].

1.2. The role of agricultural crop residues in the National Renewable Energy Action Plans

In the framework of targets fixed by Directive 2009/28/EC, each member state had to adopt a National Renewable Energy Action Plan (NREAP) detailing the mandatory national targets for in terms of sources and uses of renewable energy until 2020. The Renewable Energy Action Plans had also to specify the measures taken in order to reach those targets, including national policies to develop existing biomass resources and mobilize new biomass resources for different uses. member states had to assess the supply of domestically available biomass and the need for imports and provide an estimation of the contribution of biomass energy use in 2015 and 2020.

The contribution to primary energy production from agricultural crop residues was not requested to be evaluated separately in the NREAPs template [17] and the large majority of the Action Plans included it in the more general category of “Agricultural by-products, processed residues and fishery by-products for energy generation”. According to the Action Plans template, the by-products in this category contain straw, manure, animal fat, meat and bone meal, cake by-products (including oil seeds and olive oil cakes for energy), fruit biomass (including shells, kernel), fishery by-products, clippings form vines, olives, fruit trees and other by-products. Detailing energy contributions of these categories was not compulsory and very few member states have provided a split of agricultural and fishery by-products into the listed sub-categories.

Fig. 2 shows the aggregated data for biomass domestic supply in the EU in 2006 and estimations for 2015 and 2020. The consolidated data reported in the NREAPs shows that the overall utilized amount of residues and by-products is expected to produce almost 14.9 Mtoe (i.e., 624 PJ) in 2015 and 20.5 Mtoe (i.e., 860 PJ) in the whole EU-27. However, the estimated amount for this group of residues for energy production varies considerably among the different member states, with a maximum for Italy with 1900 ktoe (80 PJ) utilized agricultural residues in 2015 and 4900 ktoe (205 PJ) in 2020 and Slovakia with 2000 ktoe (84 PJ), both in 2015 and 2020.

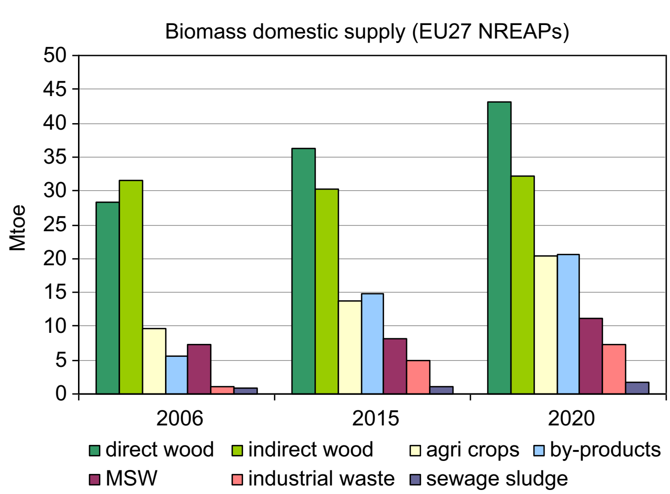

Fig. 2. Biomass domestic supply in the EU in 2006 and estimations for 2015 and 2020 in National Renewable Energy Action Plans.

1.3. Towards a geographical view of crop residues and their mobilization for energy production

This study is intended to update and extend the previous studies form Scarlat et al. [1] and Edwards et al. [13], providing a geographical assessment of crop residues resources in EU-27 and their cost-effective exploitation in typical power production plants. In Section 2 an updated statistical assessment of agricultural crop residues in EU-27 is provided for both residues production and their competitive uses (Section 2.1) and GIS data layers are employed in order to allocate geographically the processed statistical values (Section 2.2). In Section 3 the possible exploitation of residues is further analyzed: Section 3.1 focuses on modeling of feasible strategies for optimal power plant localization in harmony with geographically available residues, while in Section 3.2 results for the actual energy potentially available are provided. Finally, in Section 3.3 the need of residue mobilization is evaluated under different hypotheses. In Section 4 results are discussed in comparison with other literature studies and Action Plans, and in Section 5 conclusions and outlook are presented.

2. GIS based agricultural crop residues resource assessment

Development of a comprehensive geospatial dataset of essential agricultural and geographical information involved two main components. Data harmonization and statistical model application on residue production and competitive uses provided the numerical properties in tabular format which formed the input attribute data of the further applied spatial model. The modeled features comprise basic statistical units, land use and land cover layers, geographic distribution of crop areas and yields, and information on soil biomass productivity as supporting parameters for a more detailed spatial model of residues production.

2.1. Statistical assessment

Several data processing and modeling steps lead from the recorded, NUTS2 level crop production to the estimates of agricultural residues available for energy production purposes.

2.1.1. Agricultural crop residues production

The use of agricultural crop residues for bioenergy production requires accurate data on their availability by crop type. The crop yields depend upon specific local agro-ecological conditions (climate and precipitation pattern, soil properties, etc.), plant varieties, farming techniques, etc. Data on crop yields are directly available, while data on their residues are not, since the aim of agricultural production was mainly to maximize the yield of main food/feed product in the past. Crop residue yields are very variable and depend on plant variety, crop yield, climate and soil conditions, farming practices, harvesting techniques and the cutting height [18,19]. Residue production also depends on weather conditions and whether the crop is irrigated or rainfed, moisture availability, temperature, soil, etc. [20,21]. For this reason, hypotheses and assumptions, preferably based on consolidated literature studies are needed to design a wider regional level assessment.

The procedure performed by Scarlat et al. [1] has been chosen as reference basis for the present study. The statistical methodology employed in that study has been downscaled to the NUTS2 level all over EU-27. The total crop residue availability for energy use was calculated based on crop yields, harvested areas and

residue-to-product ratios. Specific residue-to-product ratios, depending on the crop type and crop yield were applied to the average crop production data in the decade 2000–2009 as reported by Eurostat.

It is worth noticing as one of the most crucial parameters for estimating the amount of residues available for energy production is the removal rate of residues from the terrain. Removal rates must be sustainable in order to protect soil fertility and in this study the typical values ranging from 40% to 50% have been employed, again in full consistency with Ref. [1] and the references therein. Nevertheless various authors provide different general estimations of "safe" straw removal rates in dependence of a combination of factors, including equipment limitations [22–24], plant variety and the harvest height [25], crop yields [26], soil type, slope or climate [20]. In the present status of the study the residue removal rate does not depend on the actual geographic location and the cited numbers are meant to be "typical" values representing the full Europe. Nevertheless, the model applied is fully customizable in order to take into consideration local differences in, e.g., the straw collection agricultural practices whenever data could be available.

2.1.2. Competitive uses

Data for the average numbers of livestock heads in the decade 2000–2009 at NUTS2 resolution, also coming from Eurostat, have been processed to calculate the amount of crop residues employed in animal bedding and subtracted from each NUTS2 production. Only cereal straw has been considered suitable for animal bedding, the other kinds of straw and agricultural residues not being considered as suitable for such use.

In case of negative balance, straw has not been subtracted from the adjacent regions with the hypothesis of straw traveling only very short distances inside each NUTS2. Following this approach, the amount of straw needed for animal bedding has been estimated to count about 16% of the collectable crop residues. Nevertheless such a number is much higher for some countries like Ireland and, to a smaller extend, the Netherlands. This does not mean that in principle the amount of straw currently employed for animal bedding could not be available for energy uses in the future, for example in the case of an increased market price for this commodity. The potential of agricultural crop residues are reported in kilotonnes (dry matter) at the country level in Table 1. Fig. 3 shows also produced and available crop residues in map format for NUTS2 regions.

Table 1
Crop residues produced, sustainably collectable residues and available residues for energy use in EU-27 estimated on the basis of 2000–2009 Eurostat data (kt).

	Residues produced	Collectable residues	Available residues
BE	2298	967	419
BG	7716	3370	3185
CZ	8206	3433	3164
DK	8520	3449	2923
DE	43,565	18,205	15,643
EE	738	302	259
IE	1812	727	10
EL	4969	2177	1549
ES	24,049	10,229	7845
FR	59,569	25,627	22,242
IT	20,693	9328	7906
CY	117	47	4
LV	1297	527	464
LT	3022	1232	1099
LU	143	59	30
HU	14,373	6544	6299
MT	13	5	0
NL	1472	609	99
AT	4303	1895	1525
PL	22,332	9221	8061
PT	1367	634	437
RO	19,199	8751	7927
SI	481	218	135
SK	3809	1651	1530
FI	4352	1755	1588
SE	5034	2033	1767
UK	20,441	8372	4201

2.2. Spatial allocation of agricultural crop residues

The available crop residues for each NUTS2 region have been geographically allocated on the terrain using a procedure

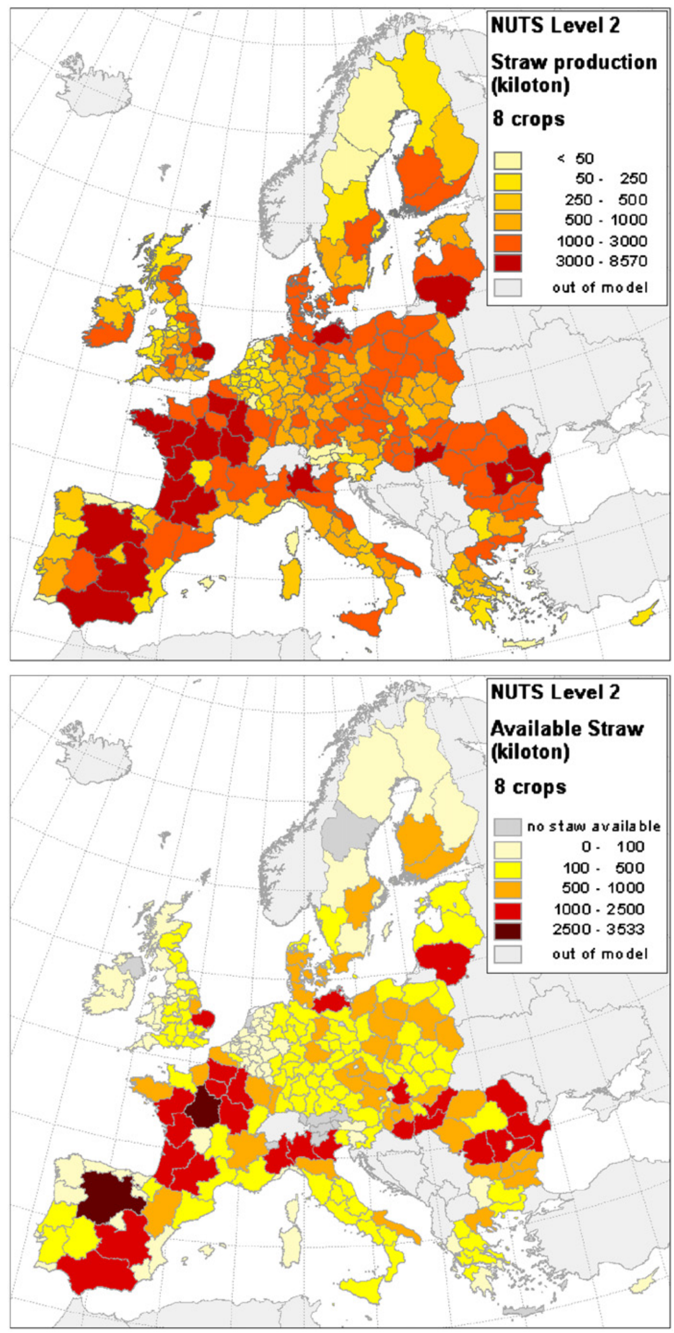

Fig. 3. Estimated amounts of produced (left) and available (right) agricultural crop residues in EU-27 NUTS2 regions.

recalling and extending the approach of Ref. [13], based on several spatial layers describing, e.g., land cover, expected biomass productivity derived from soil parameters, climatic zones and topographical conditions [27]. The main driver for the allocation process was a combined qualitative ranking-system of geographical locations within the territorial units used for statistical estimates on NUTS 2 level. According to the type of crops involved into the study, and taking the European coverage into account, only the areas labeled with the following land cover/land use classes of CORINE database were considered as "potential location" of straw production: 'Non-irrigated arable land', 'Permanently irrigated land', 'Rice fields' and 'Annual crops associated with permanent crops'. McGill M3-Cropland and Crop Data [28] were also applied as additional probability indicators of crop-specific spatial allocation of different residue resources.

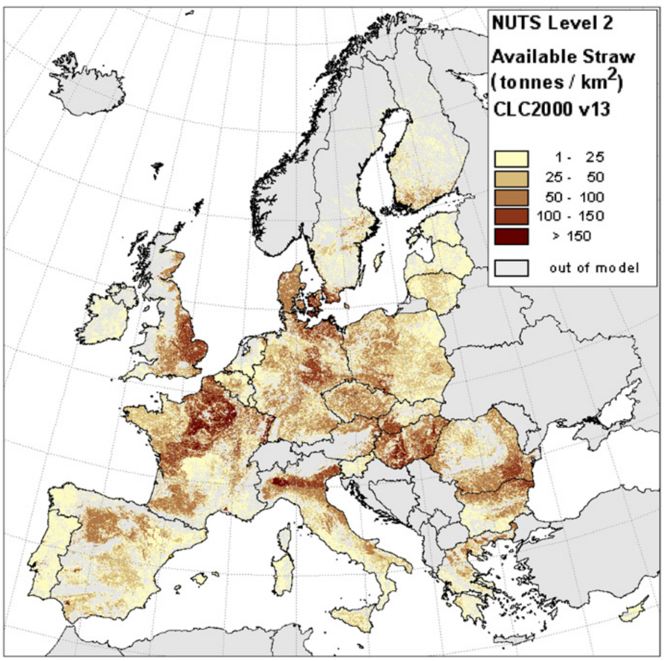

Fig. 4. Tonnes of agricultural crop residues per square kilometer potentially available for energy use in EU-27.

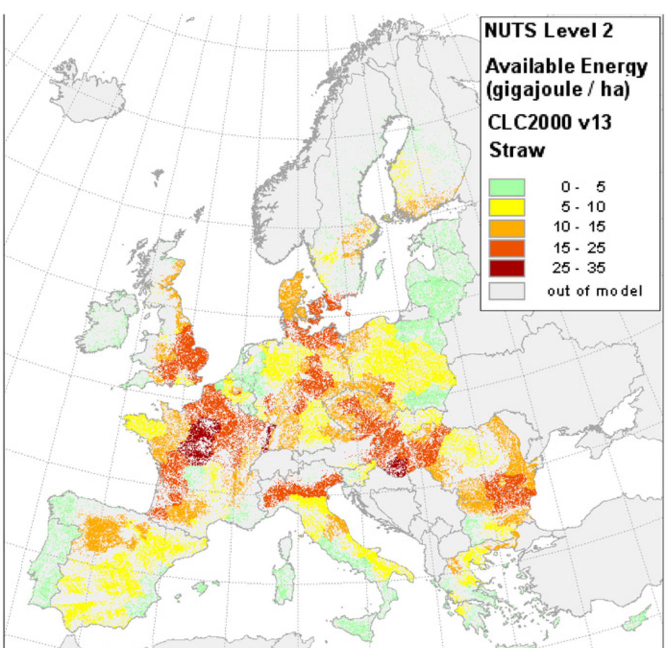

Fig. 5. Energy content in gigajoules per hectare of agricultural crop residues potentially available for energy uses in EU-27.

The procedure for spatial allocation is described in detail in Appendix A together with the characteristics of the geodata layers applied. Uncertainties of the developed methodology are rooted in the inherent properties of available spatial and statistical data sources in various scales.

Results of this allocation procedure are shown in Fig. 4 in kilogram per hectare and in Fig. 5 in potential primary energy production per hectare in gigajoules. These maps provide an indication of the most suitable European areas for agricultural crop residues energy exploitation, showing a potential concentration where crop production is relevant and competition of uses is low, as expected.

Results obtained in this section represent the theoretically available amount of crop residues after considering sustainable collection rates and competitive uses. In the next section the problem of optimizing the location of power plants in order to collect and use the highest part of this potential will be discussed.

3. Collection and transformation

The next step in the residues to energy chain estimation leads from the residues theoretically available on the terrain to the actual residues worth being collected. Indeed, the potential residues shown in Figs. 3 and 4 are not necessarily convenient for actual exploitation for energy production. In particular, there are areas where the residues left after subtracting competitive uses are too sparse to be conveniently collected to feed a power plant. For studying this issue a model of a typical power plant of its optimal allocation has been developed.

3.1. Power plants and collection points: a decision support approach

Crop residues are well known to have a noteworthy potential for energy uses and several countries are already exploiting such an additive value in different mixes and in different kinds of plants. Voytenko and Peck [29] have grouped and analyzed the key factors of the organizational structure of Swedish and Danish examples of straw-for-energy production chain ranging from small scale boilers mainly aimed at providing heat for the farm itself to large Combined Heat and Power (CHP) plants.

In the European Union, the three main operational references for plant operations are:

– *Biomass-fired power plant of Ensted, Denmark (39.7 MWe)*: This biomass-fired boiler plant consists of two boilers, a straw fired boiler producing heat at 470 °C and a wood chip fired boiler superheating the steam from the straw fired boiler to 542 °C. With an estimated annual consumption of 120,000 t of straw and 30,000 t of wood chips, this plant produces 88 MW of thermal energy including 39.7 MW of electrical power.
– *Straw-fired power plant of Ely, United Kingdom (38 MWe)*: This power station of Ely was the world's largest straw-fired power plant when it was built. It uses 200,000 t of straw per year and can also burn a range of biofuels and natural gas up to 10%. The main fuel used is cereal straw.
– *Straw-fired power plant in Sanguesa, Spain (25 MWe)*: The Sanguesa plant consumes about 160,000 t of straw and corn stover per year. The straw is supplied by farmers within a 75 km radius of the plant and the barn has a storage capacity of three days of operation.

3.1.1. Modeled power plants

Following the idea that in a continent hungry for energy, especially renewable energies, most efficient uses should come first, in this work we have prioritized the use of crop residues in CHP plants. Considering the fact that heat is more difficult to be dispatched than energy and the production of a large amount of thermal heat would be more difficult to be properly exploited, in the present study a movement of the bioenergy production towards plants somewhat smaller than the cited ones was supposed. A CHP plant with a capacity of 50 MW of thermal input, needing about 100 kt/yr of raw material was considered "typical" for the upcoming EU bioenergy market. Such a power plant is expected to show an efficiency of 25–30% for electricity production and about 55–60% as far as heat is concerned [29]. This plant capacity has been considered here as an optimal size providing a good balance between operational costs and revenues given the logistic and feasibility constraints related to the mobilization of a low-density energy source such as crop residues and the need to find a suitable client for heat production.

3.1.2. Spatial location of power plants: geospatial constraints

In this work a location for a 'typical' power plant was considered suitable if the necessary resources could be found in the physical radius of 50 km, corresponding to a maximum travel distance of 70 km, given the typical European road deviousness factor of 1.4. An additional physical geographical constraint on slope gradient (not greater than 20%) was applied positioning a feasible "typical" CHP power plant. On the contrary, in the present study, no constraints on the presence of near-by heat demand able to absorb the thermal production of the plant itself have been imposed, because of the lack of harmonized relevant geodata. For this reason, the full exploitability of the heat production could not always be assured.

3.1.3. Spatial location of power plants: optimization strategies

Once a set of suitable geographical locations for power plants location have been selected on the basis of the former geographical constraints, they have to be ordered to prioritize their exploitation. Two different procedures have been developed each reflecting a different approach to the problem: an optimized approach where all suitable locations in the continent are ranked following their production potential and a randomized one where a strict ranking is absent and suitable locations are exploited following a mostly random scheduling. Computational details of the two approaches are summarized in Appendix B.

The two exploitation strategies here considered are meant to reproduce two different strategies. In the first case a totally rational planning behind plants location is assumed and plants are positioned assuring the optimal use of feedstock. While such a strategy puts emphasis on the most productive areas, it could be questioned how realistic it is. The main limitation of this method, is exactly the assumption of the existence of a large scale planning and a strongly rationale design of the process of plant allocation while in the reality these aspects are often left to market forces. For this reason a second approach to the plant allocation was also developed.

The randomized approach represents the situation where a strong planning strategy is absent and investors planning to build power plants act independently. Randomization incorporates the assumption of the priori lack of information on where these actors will decide to play first. Nevertheless, the repetition of the allocation procedure for several times with different sequences of potential location points, provides a *probability distribution* of locations, even more useful than the evaluation of optimal (and sometimes unrealistic) values. Obviously, even this approach could be questionable from other aspects: e.g., in an area of very dense agricultural production it could make sense for the investors profiting of the availability of resources and the consequent

Table 2
Number of plants, primary energy produced and percentage of residues actually exploited under the two plants allocation hypothesis examined.

	Randomized allocation	Optimized allocation
Number of plants	834–852	847
Primary energy (PJ)	1510–1540	1490
Percentage of available residues actually used for energy (%)	84.4–86.0	83.1

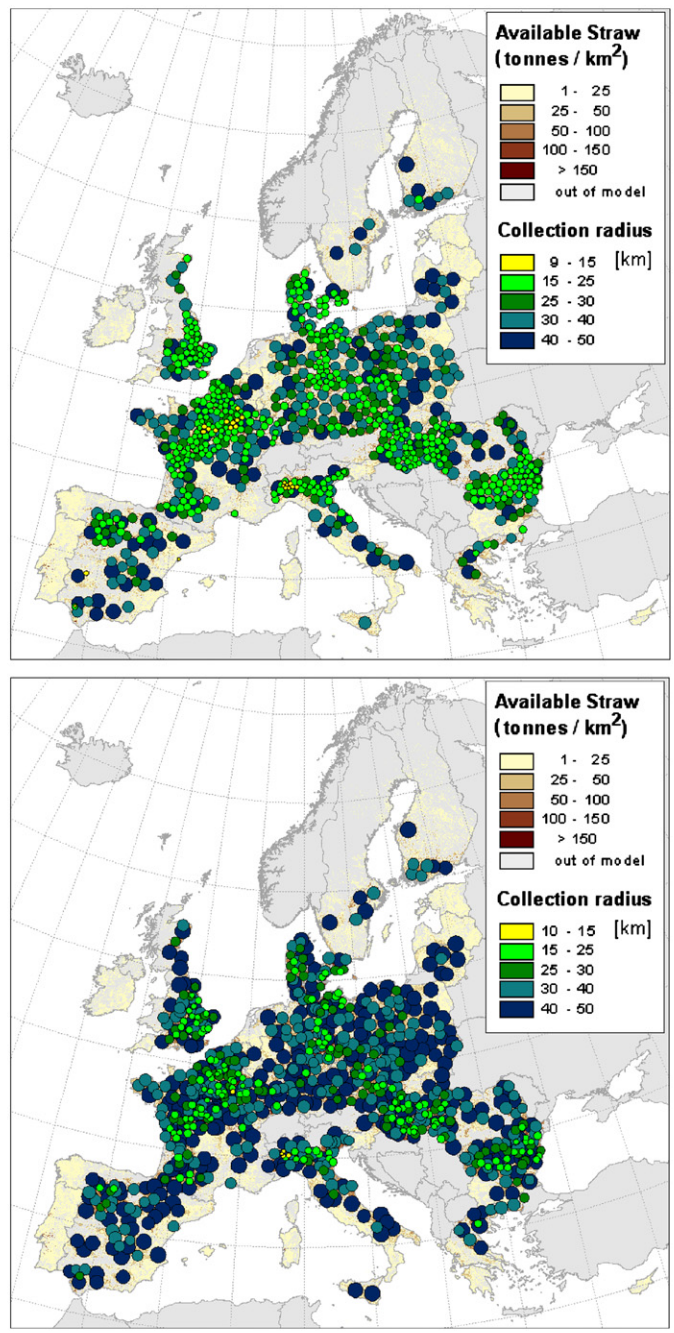

Fig. 6. Optimized (left) and randomized (right) distribution of modeled power plants in EU-27. Collection radiuses are also shown in actual size.

lower transport costs setting up plants larger than the standard one here considered. Similarly, other developers might opt for building a smaller capacity plant in a region where resources are less dense, while keeping the collection distance, and thus the logistics costs, within a reasonable limit.

In summary, the two approaches suggested here, the optimized and the randomized ones, suffer possibly opposite biases. For this reason, they could be considered as upper and lower bounds, more than pretending to represent into details the reality of the complex process of locating power plants in a densely populated and constrained region like Europe.

3.2. CHP plants and energy production

In the present study the optimized plants localization approach was applied and compared with a Monte Carlo set of simulations for the randomized localization approach where the full sequence of plants positioning procedure was repeated 20 times in order to obtain 20 different but equally likely "maps" of crop residues power plants in EU-27.

Table 2 shows the number of plants allocated and the overall energy produced with the two discussed methodologies while Fig. 6 shows the geographical distribution of modeled power plants in EU-27 resulting from the optimized approach (left) and the randomized approach (right) in one realization.

In the optimized approach 847 power plants were positioned all over Europe collecting the 83.1% of the total crop residues theoretically available for energy production, while the randomized approach allowed to place a number of CHP plants between 834 and 852 with a collection capacity ranging from 84.4% and 86% of the total theoretically available potential shown in Figs. 3 and 4.

It is interesting to notice how a less optimized approach allows exploiting a slightly higher amount of raw resources. This is due to the fact that in the surrounding of a randomly placed plant could be heterogeneous and lands characterized by higher and lower productivity are both likely to be mixed together. On the contrary, in the optimized approach, a plant is likely to be placed in the highest production zones and leaves other areas unexploited. In this way, randomly placed plants are more likely to exploit the lower production areas that are typically neglected by the optimized power plants.

Fig. 7 shows how plants are distributed among the European countries in both the approaches.

Obviously, countries with the highest available amount of residues can allocate the larger number of power plants. Nevertheless, the efficiency in utilization of resources can be different in the different countries: Fig. 8 shows the ratio between crop residues actually used for energy in each country and its potentially available resources according to data shown in Figs. 4 and 5. Under the proposed assumptions, this fraction can vary between 0.8 and 0.95 in larger and more productive countries. It is also worth noticing as residues are not necessarily transformed in energy in the same country where they are collected: the methodology applied fully allows transnational movements of raw material, provided that the maximum mobilization radius supposed (50 km) is respected.

3.3. Mobilization

Fig. 9 shows the crop residue mobilization needed in terms of transported material by covered distance (tonnes × kilometers, tkm) as a function of the gross potential energy produced (GJ) for the two different methodologies of plant allocation explored in this study. Fig. 9 shows that allocating plants following the optimized approach allows a substantial saving in terms of resources mobilization especially in the case of firstly situated plants. Indeed, the first power plants are placed in very productive areas, so their actual collection radius is much smaller than the maximum of 50 km and thus their fuel should travel only for short distances from the arable lands close by.

In Fig. 10 the marginal mobilization needs, i.e., the additional tonne-kilometers needed to produce an additional gigajoule of energy from crop residues are also shown. For the randomized plant allocation this parameter varies almost randomly in the range between about 500 and 2500 tkm GJ^{-1} while on the contrary, marginal mobilization needs in the case of the optimized approach follow a clear increasing path moving from about 400 tkm GJ^{-1} for the first coming plants up to about 2000 tkm GJ^{-1} for the last plants entering in the production and then placed in the less productive areas. Probably none of the two models for plant allocation here compared represents the reality completely and the actual mobilization needs of agricultural crop residues might be between that the two models predict.

Finally, it is worth noticing that in the present study no attempt has been done to put the mobilization in relation to actual costs of raw material transportation due to the high variability among member states. Nevertheless the revealed difference in the required freight transport between the two plant allocating philosophies investigated here is quite important: the optimized planning could lead to 25–30% less transport related emissions and costs if compared with the randomized site selection.

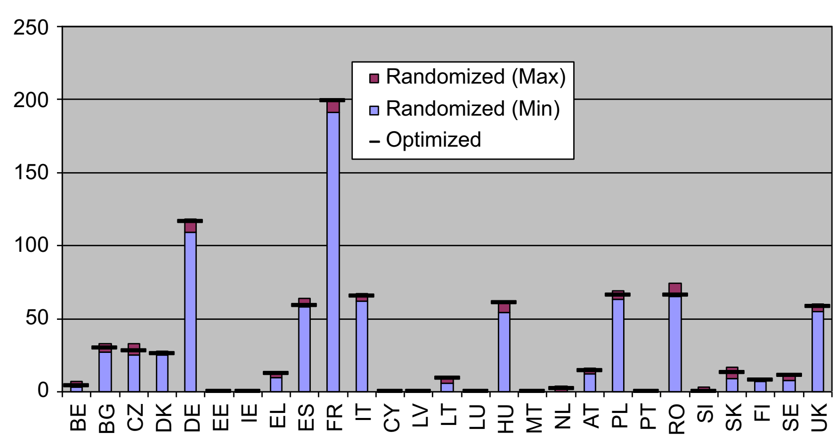

Fig. 7. Distribution of power plants among EU countries. Minimum and maximum values obtained for each country with the randomized approach are shown together with the value obtained in the optimized approach.

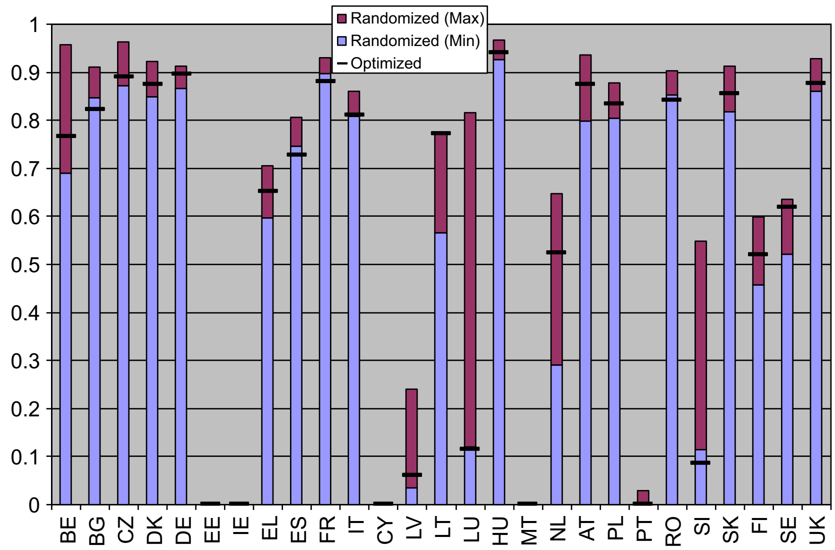

Fig. 8. Fraction of available straw actually exploited for energy uses in the EU countries. Minimum and maximum values obtained for each country with the randomized approach are shown together with the value obtained in the optimized approach.

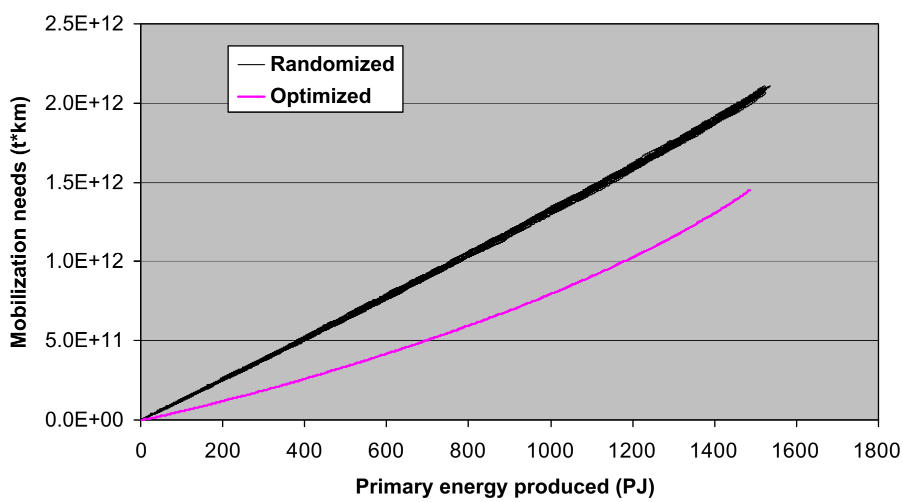

Fig. 9. Mobilization needs (tonne-kilometers) as a function of the primary energy produced.

4. Discussion

The presented work estimates the possible contribution of agricultural crop residues to the EU-27 energy mix on the basis of the following steps: residues production, sustainable residue collection, competitive uses of residues, spatial allocation, mobilization and conversion into energy. Each of the steps several assumptions were taken, with some of them being somewhat optimistic, e.g. the hypothesis that all the raw material not left on the ground for preserving the soil quality and not diverted to animal bedding is potentially available for energy uses or that the collected residues are transformed into energy in highly efficient CHP plants. These hypotheses only partially reflect the often less efficient reality. For this reason, these results should be better interpreted as upper limits of the actual feasible energy production from agricultural crop residues. Nevertheless, the order of magnitude of such a production potential can be compared with the potential declared in the NREAPs by EU member states.

As already stated, only a very limited number of NREAPs contains the non compulsory details about agricultural crop resides use for energy purposes. Table 3 shows the values reported in the NREAPs of Netherlands, Denmark, Finland, France and Ireland for crop residue-based energy production in 2006 and the projections for 2015 and 2020 in units of kilotonnes of oil equivalent (ktoe) compared with the potential estimations coming from this study (the average of the "randomized" values is actually shown)

It is interesting to see that with the exception of Ireland, all the countries are reporting an expected crop residues exploitation in 2020 lower than the upper limit value estimated in this study. Nevertheless, the two countries (Denmark and the Netherlands) declaring in the NREAPs an explicit strong interest for straw-to-energy supply chain have provided an estimated value quite close to the one obtained in this study. On the contrary for France and Finland (Table 3), a more limited exploitation of crop residues resources is indicated, probably also because of the large availability of biomass from other resources, such as forest biomass.

On the contrary, in the case of Ireland, the projections contained in the NREAP provide a certain amount of crop residues to be available for energy production in 2020 while the feasibility evaluation developed and presented in our study has estimated a null potential. An analysis of literature cited in the Irish NREAP shows that national estimates are based on the volume of raw crop residues being quite close to the one obtained also in this

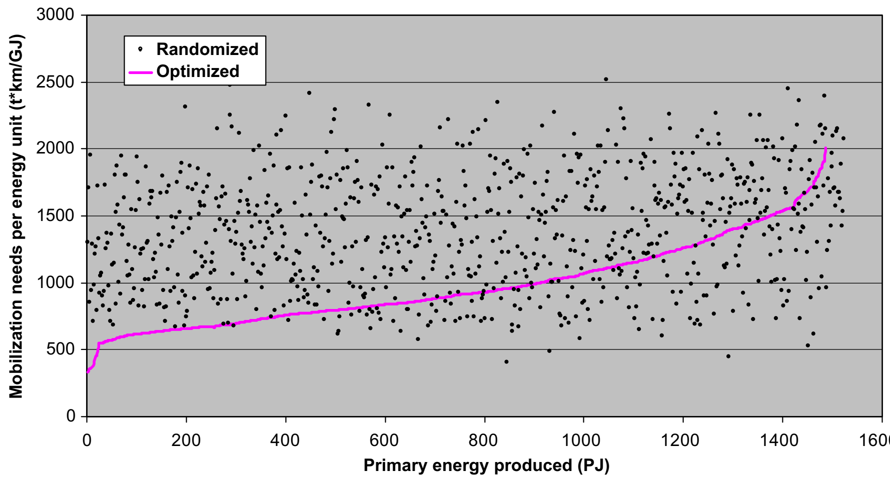

Fig. 10. Marginal mobilization needs (tonne-kilometers) per gigajoule of energy produced.

study, while the estimation of crop residues needed for non-energy purposes seems much smaller than it was supposed in this study.

5. Conclusions

The main logic components of the processing chain leading from crop residues to energy production in EU-27 have been analyzed in this paper. The potential energy production was estimated following several steps starting from regional statistical data available for crop production in the decade 2000–2009. Consistent residues-to-crop ratios were defined and sustainable removal ratios and competitive uses of crop residues have been also considered in the calculations. A higher resolution spatial distribution of crop residues theoretically available in Europe for energy purposes has also been provided, then the generated dataset formed the input geographic information to the elaborated statistical model for decision supporting and planning evaluation. Two different methodologies for allocating crop residues fed power plants have been developed and applied in order to estimate the fraction of potentially available crop residues possible to be efficiently transformed into both electricity and heat in appropriate CHP plants.

The results have shown that EU member states can count on very different crop residue resources mainly in function of the importance of their agricultural system and the development of economic sectors competing for the raw materials (e.g. animal bedding). As a general result, the analysis has shown that around 830–850 CHP residues fed plants of a "typical" thermal capacity of 50 MW are possible to be supplied in EU-27, providing an average amount of primary energy close to 1500 PJ/yr and allowing an exploitation of 83–86% of the residues theoretically available for energy production.

Furthermore, the crop residues mobilization needs have been estimated in terms of tonne-kilometers and two different estimates of the mobilization needed for a full potential exploitation of 1.5×10^{12} tkm in the case of optimized plant allocation and of 2×10^{12} tkm in case of randomized plant allocation have been obtained for the full potential mobilization while marginal mobilization has been estimated to range from 400 to 2500 tkm GJ^{-1}.

The results obtained in this study have been compared with the estimations reported by several EU member states that have also provided more detailed, specific data for agricultural residues in their National Renewable Energy Action Plan. The comparison has shown that the member states usually reported forecasts smaller than the estimates contained in this study while they were very close if the country was strongly committed to develop the straw-to-energy supply chain. Such a comparison confirms the suitability of the data provided here as upper limits of energy obtainable from mature and optimized crop residues exploitation.

Table 3
Amount of primary energy (ktoe) obtained from residues as reported in National Renewable Action Plans of some European countries. The member states of the European Union not included in the table have not reported specific values.

	Year 2006	Year 2015	Year 2020	Estimate
NL		29	53	69
DK	443	500	1000	1130
FI	0	36	71	349
FR		500	1000	8512
IE		49	260	0

As a final remark, it could also be noted in this study that a GIS-based decision supporting tool made by the geographical data layers of residues and the optimization tools has been developed. The main parameters can be easily changed and tuned to describe situations different form the ones described here in order to test different options for making crop residues an even more attractive energy resource. Further applications and refining of the tool are expected to be at the core of future work focusing several possible lines like, e.g.:

- Sustainable straw collection rates could be improved and better specified in order to connect them with soil features, climate zones and local practices.
- Biophysical parameters of the crops could also be considered in order to better connect residues-to-product ratios with the quality of crops actually present on the terrain.
- The demand for heat should also be included in the maps set in order to prioritize CHP plants locations assuring an efficient exploitability of the heat produced.

Disclaimer

The views expressed in this paper are purely those of the writers and may not in any circumstances be regarded as stating an official position of the European Commission.

Appendix A

The spatial allocation of available agricultural crop residues amount by NUTS2 regions were completed in five main geoprocessing steps. Since the available primary data on European land cover raster data (Corine land cover 2000, CLC2000) did not distinguish among different crops producing residues, only rice fields form a individual class, first the geographical area of croplands in general was delineated based on version 13 of the CLC2000 raster in 100 m resolution using the class code of the relevant land cover types. Preparing further processing steps there were three layers separated showing potential area for all the sources of straw production (CLC_CROP8LAND), and two auxiliary layers separating the cells of arable lands (CLC_CROP7-LAND) and rice fields (CLC_RICEFIELD).

CLC_CROP8LAND = con (clc2000v13 in {12, 13, 14, 19, 20, 21}, 1, 0)

CLC_CROP7LAND = con (clc2000v13 in {12, 13, 19, 20, 21}, 1, 0)

CLC_RICEFIELD = con (clc2000v13 in {14}, 1, 0)

The calculated available residue amounts for each crop by NUTS2 regions were evenly distributed in the corresponding cells in the second processing step.

Since the available global data set [28] of net primary production covered the same period (year 2000), the McGill M3 Crop Data Level 2 (crop yield in tonnes per ha) has been applied in the third processing step weighting between cell values having the average values of straw production within the NUTS2 regions. The original resolution of this auxiliary data was coarser (5 min) than the processed raster data in 100 m resolution but the borders of measuring units were not identical with the European statistical units, thus the alternating crop yield values could be applied as productivity indicators within the NUTS2 regions. In the fourth processing steps the spatial distribution of available straw amount has been modified using the results of a complex European biomass productivity model [27] in the weighting.

The prepared 100 m resolution raster data set was aggregated in the final step using a function that partitioned the input 100 m resolution grid into blocks (1 km) the sum of the values for the specified cells (defined by the neighborhood parameters: square, 10×10) within the blocks calculated and sent to the cell locations in the corresponding blocks on the output grid, that was resampled also physically from 100 m to 1 km.

Appendix B

The two approaches to power plant location studied can be described as follows:

1—Optimized approach. Following and extending the approach of Ref. [13] the crop residue map presented in Section 2 is scanned in order to identify the area with the highest straw productivity: for this goal around each grid-point of the cell-based map a circular collection area of radius r was defined as the smallest area containing at least the minimum straw need for the "typical" power plant modeled (100 kt). Points with collection radius $r \leq 50$ km were further scanned in order to identify the point where the raw material mobilization requested for unit of energy produced, in terms of t km/GJ, reached the smallest value and a "typical" CHP power plant was placed to the local minimum point. Following the plant positioning, all the residues included in the circle were taken out from the map and the full procedure (scanning the map, setting the collection areas and selecting the optimal one) was repeated until it was not possible to find any circle of radius $r \leq 50$ km containing enough raw material to feed the "typical" plant.

2—Randomized approach. In the randomized approach a large set of potentially suitable locations for power plants buildings is defined on the basis of geographical constraints only (e.g. terrain slope). These potential locations are then put in a random order and examined one after the other in the following way: circles of increasing radius, from 1 to 50 km, are drawn around the potential location point. If the circle arrives to contain the requested 100 kt of collectable residues, for a value of $r \leq 50$ km the procedure stops, and all the residues produced inside the collection radius r are taken out form the map the next random potential location is examined. On the contrary, if the collection circle reaches 50 km without containing the necessary 100 kt of residues, the potential location is discarded, no residues are taken out form the given area and the next random potential location is examined. The overall procedure ends when all potentially suitable locations have been examined.

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